ROBOTIC PLANETARY SURFACE EXPLORATION

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Abstract: This extended abstract is a brief text of speech given by the author as the opening plenary talk at the 3rd IFAC Symposium on Intelligent Autonomous Vehicles. After a brief introduction about JPL's past, present, and future missions, it presents Sojourner rover and its accomplishments as well as JPL's research on Long Range Science Rovers. Please see references 1, 2, and 3 for more information.

1. INTRODUCTION

Managed for NASA by the California Institute of Technology, the Jet Propulsion Laboratory is the lead U.S. center for robotic exploration of the solar system. JPL spacecraft have visited all known planets except Pluto (a Pluto mission is currently under study). In addition to its work for NASA, JPL conducts tasks for a variety of other federal agencies. In addition, JPL manages the worldwide Deep Space Network, which communicates with spacecraft and conducts scientific investigations from its complexes in California's Mojave Desert near Goldstone; near Madrid, Spain; and near Canberra, Australia. JPL employs about 6000 people.

1.1 Past Missions

JPL developed spacecraft have investigate Venus (Mariners 2, 5, 10, and Magellan), Mars (Mariner 4, 6, 7, 9, Viking 1 and 2 - Orbiters/Landers and Mars Observer), the Moon (Surveyor Moon Lander), and Mercury (Mariner 10). These missions have completed their investigations and have provided a vast amount of new data for planetary scientists to better understand the formation of the solar system and its composition.

1.2 Present Missions

At the present time several spacecraft are exploring the solar system. Cassini, perhaps the last large JPL spacecraft, is on its way to Saturn and its moon Titan. Galileo spacecraft is finishing its exploration of Jupiter and its moons. Mars Global Surveyor is orbiting Mars and sending very high resolution images of the red planet. Mars Pathfinder and its Sojourner Rover have basically finished their mission after the most spectacular landing and roving on Mars. Voyagers 1 and 2 have been flying for over 20 years. Voyager 1 is the farthest human made object from the Earth. Ulysses Mission to the Polar Regions of the Sun is in progress.

Figure 1. Explorer 1 was the first American earth-orbiting satellite, launched on January 31, 1958 -- approximately 3 months after the Russians launched Sputnik. It was a joint project of the California Institute of Technology Jet Propulsion Laboratory and the Army Ballistic Missile Agency in Huntsville, Alabama.

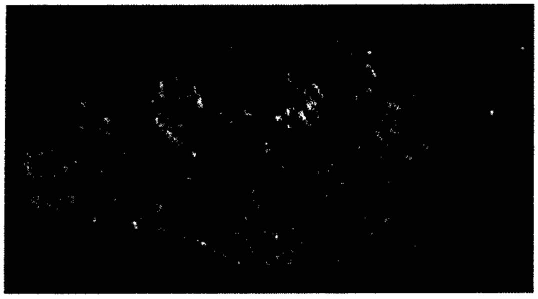

Figure 2. This computer-generated perspective view of the an impact crater on Jupiter's moon Europa was created using images taken by NASA's Galileo spacecraft camera when the spacecraft flew past that moon on Feb. 20 and Dec. 16, 1997. Pwyll, about 26 kilometers (16 miles) across, is unusual among craters in the solar system, because its floor is at about the same elevation as the surrounding terrain. Moreover, its central peak, standing approximately 600 meters above the floor, is much higher than its rim. This may indicate that the crater was modified shortly after its formation by the flow of underlying warm ice.

1.3 Future Missions

JPL has planned to develop numerous spacecraft to explore the solar system in the coming decade. There is a paradigm shift from developing expensive large spacecraft with many science instruments to many inexpensive spacecraft with fewer science instruments. These new generations of spacecraft will also use cutting edge technology which normally was not used in the past for flagship missions.

At the present time three New Millennium Program missions namely Deep Space 1, Deep Space 2, and Deep Space 4 are planned to explore an asteroid, send a probe that will penetrate the Martian surface, and rendezvous with a comet and scoop up a sample of the nucleus, and return to Earth.

The Stardust mission will bring back to Earth a sample from another comet.

The Surveyor Program consists of a series of missions that will explore Mars and bring samples to Earth. Current plans call for launching two spacecraft every 26 months, one orbiter and one lander. The first of these is the '98 mission which will have a lander with a robotic arm. The robotic arm will be used to scoop soil and perform in-situ analysis. The 2001 and 2003 missions will have long range rovers with several science instruments onboard. These rovers will explore Mars by traversing many kilometers on the surface. In addition they will be drilling rocks and caching samples for the 2005 sample return rover.

The 2005 mission will land a spacecraft very close to one of the previously flown rovers. A small rover will leave the lander and find the 2001 or 2003 rover and transfer the samples to the lander for return to Earth. It is expected that samples from Mars will be available for testing on Earth by the 2007.

2. ROVER DEVELOPMENT AT JPL

JPL has been developing rovers for over 20 years. Several large rovers were developed and tested for possible Mars missions in 1970s and 1980s. Robby was the last large rover that demonstrated autonomous path planning capability and had a six degrees of freedom robotic arm for sample manipulation.

In late 1980s smaller rovers were developed at JPL. These were called Rocky series rovers due to the fact that their mobility system utilized a novel JPL invented mechanism called rocker-bogie. The rover's wheels and suspension use a rocker-bogie system that is unique in that it does not use springs. Instead, its joints rotate and conform to the contour of the ground, providing the greatest degree of stability for traversing rocky, uneven surfaces. Rocky 3 and 4 rovers were the direct predecessors to the Sojourner rover. These rovers demonstrated and established the feasibility of a small rover for a mission to Mars.

3. PATHFINDER MISSION AND SOJOURNER ROVER

The Pathfinder mission was an inexpensive science and technology mission to restart the exploration of Mars after a relatively long period since the Viking missions in mid 1970s. The mission consisted of a lander and a rover. The Sojourner rover was the first rover to explore the Martian surface. It was launched in December of 1996 and landed on Mars on July 4, 1997.

The lander was a crucial element of the mission and for the rover operation. The communication to the rover was through the lander. The lander's stereo cameras were used to take panoramic images of the area surrounding it and was used by the rover operators on Earth to determine waypoints for rover's movements.

The rover (See Figure 3) has six wheels. The wheels are 13 centimeters (5 inches) in diameter

4. ROVER RESEARCH FOR FUTURE MISSIONS

As was mentioned earlier, the Surveyor Program includes Long Range Science Rovers (2001 and 2003 missions) and a sample return rover for 2005. Here we will provide information regarding JPL's research for the Long Range Science Rovers only.

Our goal is to develop technologies that overcome the limitations of the Sojourner rover as well as to introduce new capabilities currently not supported. These are:

- Increasing rover autonomy so that the number of science experiments per uplink command is increased, resulting in more science data.
- Developing the ability of the microrover to traverse long distances by (a) integrating a celestial sensor (e.g., a sun sensor) to determine the rover's orientation and (b) developing a deployable mast mounted camera system to send panoramic images of the surrounding area to the ground control personnel.
- Integrating representative science instruments onto the rover.
- Developing a distributed Internet-based rover interface so that scientists can make science experiment requests and the general public can view return images immediately.
- Testing and validating these technologies in realistic settings and with planetary scientist participation.

4.1 The Rocky 7 Rover

In this section we provide the Rocky 7 rover configuration, and we detail the constituent components. Figure 4 shows Rocky 7 in the JPL Mars Yard. The Mars Yard is a 15 X 25 meter outdoor test area that closely simulates Mars-like terrain constructed on the basis of statistical analysis of images taken by Viking Landers I and II.

One important consideration in developing Rocky 7 has been its flight relevance. This has severely constrained its size, mass, and power. The size of the rover is dictated by the size of the payload envisioned for future missions. Rocky 7 measures 48 cm wide, 64 cm long, and 32 cm high. The wheel diameter is 13 cm. The peak power available on Mars using a solar panel is 15 watts. Since commercial components are used on Rocky 7, its current power consumption is higher than 15 watts, but there are flight equivalent components that can reduce the power required to 15 watts.

4.2 The Mobility System

The mobility system is a modification of the Rocker-Bogie design used in previous rovers at JPL . It consists of two rockers hinged to the sides of the main body. Each rocker has a steerable wheel at one end and a smaller rocker at the other end.

Unlike its predecessors Rocky 3 and 4 (and the Sojourner flight rover) that have four steerable wheels, Rocky 7 has only two.

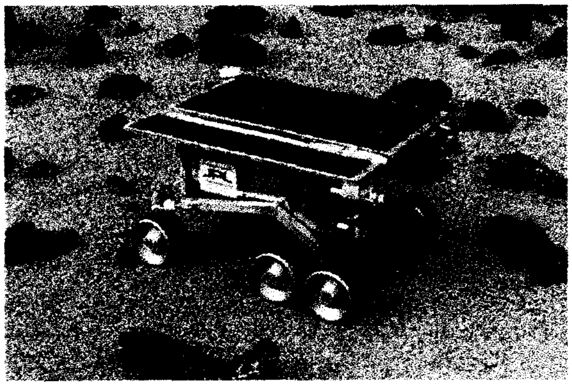

Figure 4. Rocky 7 Rover in JPL Mars Yard shown with stowed mast and sampling arm.

4.3 The Sampling System

One significant improvement over previous Rocky series rovers is the incorporation of a sampling device on Rocky 7. This lightweight (650 gm) sampling arm consists of a two-DOF manipulator (32 cm long) that is attached to the front of the rover and can reach 10 cm below the ground surface. Figure 5 shows the sampling arm with an acquired soil sample. In addition to its sampling function, the arm is used to deliver light to an optical fiber via a pair of mirrors. This is accomplished by configuring the scoops to a position and exposing a normally closed hole. The optical fiber carries the light (image) to a point spectrometer located inside the rover chassis.

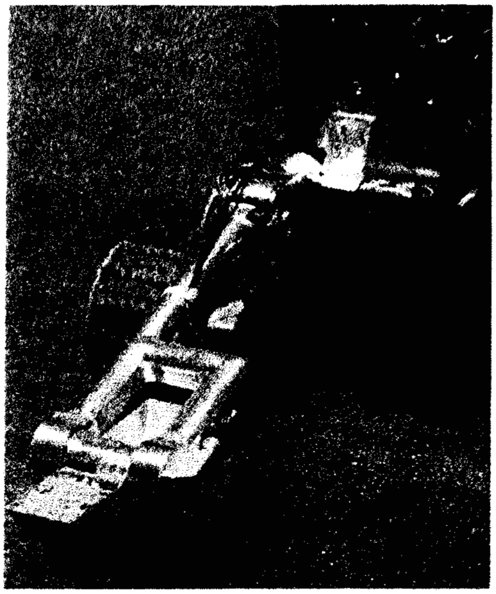

Figure 5. Sampling arm of Rocky 7 Rover

The arm can be deployed for three different operations: digging, dumping, and spectrometer data acquisition. Before each deployment, the rover checks for possible collision of the arm with obstacles (rocks) by using its onboard stereo vision system and automatically positions itself to avoid them. For a dig operation, the vision system also processes the images of the area in front of the rover to determine if the ground is soil-like by analyzing the image texture and elevation information. It then deploys the arm and lowers it until contact is made with the surface by monitoring the arm motor current. After the dig operation, it positions the scoop that collected the sample and takes its image. The rover then compares this image against the one taken just before the dig operation. If it detects enough difference between these two images, the rover reports success and completes the dig operation by closing the scoops and stowing the arm. Otherwise it does an automatic dump, stows the arm, and reports failure. Similar autonomous checks are performed for a dump operation.

4.4 Sensors

Several sensors are used for navigation. A sun sensor developed by Lockheed Martin, called the Wide Angle Sun Sensor (WASS), with a 160 deg field-of-view provides heading information. This sensor is critical for rovers that must traverse long distances in a specified direction. Figure 6 shows the sun sensor which is mounted on the solar panel of Rocky 7.

Figure 6. Wide angle sun sensor

A rate gyro and an accelerometer are also used on this rover. The rover is equipped with seven CCD cameras, two at each end, for the perception system and three on the mast.

4.5 The Perception System

To simplify the perception system hardware, Rocky 7 uses passive stereo vision for hazard detection, unlike its predecessor, which used a laser striping system in conjunction with multiple monocular cameras to detect obstacles. The stereo vision system uses a pair of cameras with wide angle lenses to allow viewing of both the manipulator and its actions, as well as to permit imaging of rocks and other hazards extending from near the rover to a little above the horizontal.

4.6 The Navigation System

The Rocky 7 navigation strategy is based on operator waypoint designation and autonomous behavior based navigation for movement to the specified targets. Two modes of operation are possible.

1. Lander-based navigation: This is the mode where the rover is in the field of view of the lander. And is similar to the Sojourner rover operation.

2. Landerless navigation: When the rover is no longer close to the lander, it is commanded to raise its three DOF mast and acquire panoramic images. This mast also is used for pointing and placement of science instruments and rover self-inspection.

and made of aluminum. Stainless steel treads and cleats on the wheels provide traction and each wheel can move up and down independently of all the others. Three motion sensors along Sojourner's frame can detect excessive tilt and stop the rover before it gets dangerously close to tipping over. Sojourner is capable of scaling a boulder on Mars that is more than 20 centimeters (8 inches) high and keep on going.

The microrover is powered by a 0.22sqm solar panel comprised of 13 strings of 18, 5.5mil GaAs cells each. The solar panel is backed up by 9 LiSOCL2 D-cell sized primary batteries, providing up to 150W-hr. This combined panel/batteries system allows microrover power users to draw up to 30W of peak power (mid-sol) while the peak panel production is 16W. The normal driving power requirement for the microrover is 10W.

Microrover components not designed to survive ambient Mars temperatures (minus 110degC during a Martian night) are contained in the warm electronics box (WEB).

Control is provided by an integrated set of computing and power distribution electronics. The computer is an 80C85 rated at 100Kips which uses, in a 16Kbyte page swapping fashion,

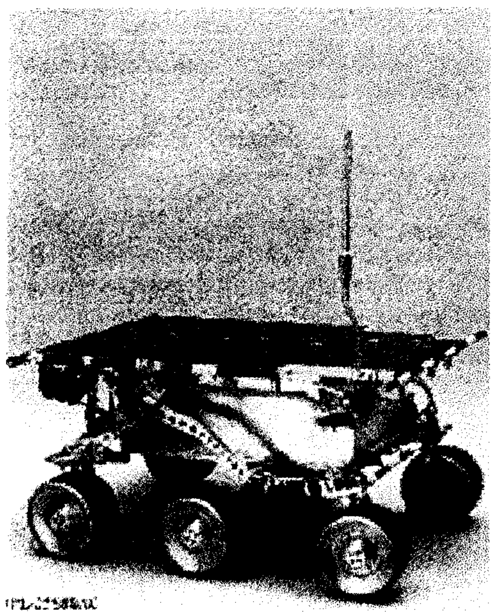

Figure 3. Sojourner Rover

176Kbytes of PROM and 576Kbytes of RAM. The computer performs I/O to some 70 sensor channels and services such devices as the cameras, modem, motors and experiment electronics. Vehicle motion control is accomplished through the on/off switching of the drive or steering motors. An average of motor encoder (drive) or potentiometer (steering) readings determines when to switch off the motors. When motors are off, the computer conducts a proximity and hazard detection function, using its laser striping and camera system to determine the presence of obstacles in its path.

The vehicle is steered autonomously to avoid obstacles but continues to achieve the commanded goal location. While stopped, the computer also updates its measurement of distance traveled and heading using the averaged odometry and on-board gyro. This provides an estimate of progress to the goal location.

Command and telemetry is provided by modems on the microrover and lander. The microrover is the link commander of this 1/2 duplex, UHF system. During the day, the microrover regularly requests transmission of any commands sent from earth and stored on the lander. When commands are not available, the microrover transmits any telemetry collected during the last interval between communication sessions. The telemetry received by the lander from the microrover is stored and forwarded to the earth as any lander telemetry. In addition, this communication system is used to provide a "heartbeat" signal during vehicle driving. While stopped the microrover sends a signal to the lander. Once acknowledged by the lander, the microrover proceeds to the next stopping point along its traverse.

After landing, the microrover was deployed from the lander and begin a nominal 7 sol (approximately 7 day) mission to conduct technology experiments such as determine wheel-soil interactions, autonomous navigation and hazard avoidance capabilities, and engineering characterizations (thermal control, power generation performance, etc.). In addition, the microrover carried an alpha proton x-ray spectrometer (APXS) which when deployed on rocks and soil provided element composition. Lastly, to enhance the engineering data return of the MPF mission, the microrover imaged the lander to assist in status/damage assessment.

The mission was successful in completing all its primary and secondary objectives. The rover traversed 104 meters, almost completely circumnavigated the lander and returned 28 Mbytes of image and non-image data.

The scenario for long range traverse consists of moving in the indicated direction, using the sun sensor, and periodically (e.g., ~100m to 200 m) transmitting panoramic images to the ground station. The ground station will provide new commands to either continue to traverse in the same direction or change direction. If the site is of interest to scientists, the site survey commands is issued.

Figure 7. Rocky 7 shown with deployed mast

4.7 Science Instruments

An important objective of our research in developing rovers is to understand not only the mobility, navigation, and control issues, but also to consider problems associated with the integration of science instruments, and their onboard operation and data reduction. Currently, Rocky 7 has five science instruments: a point reflectance spectrometer, a wide field of view spectral imager, a close-up spectral imager, Near IR Point spectrometer, a Moessbauer spectrometer, and an Iron Nuclear Resonance Magnetometer Spectrometer

5. THE ADVANCED OPERATOR INTERFACE

We have developed a ground control station to command the rover remotely and receive data from it. The operational scenario is based on the rover down-linking science data and stereo panoramic image pairs. These data along with camera parameter information are used to develop terrain maps. The interface is Web based and consists of viewing an image taken by a rover camera. An operator can point to and click on any point on the image and obtain the coordinates of the point. This interface allows a scientist to select science targets from his or her home institution by using any computer platform.

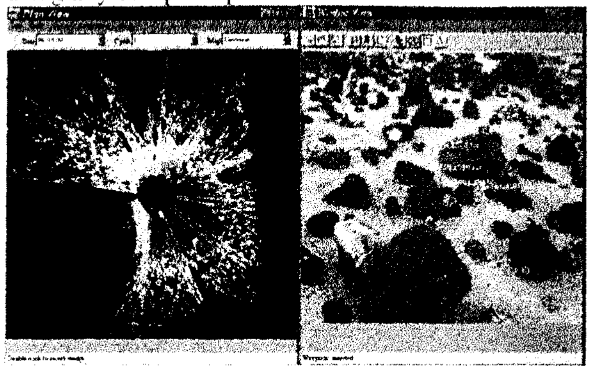

Figure 8. Web based operator interface.

6. FIELD TESTING OF THE ROCKY 7 ROVER

In order to understand the performance of the Rocky 7 Rover in a Mars-like terrain, several field tests have been performed. These field tests are collaborative activities between the Rocky 7 research team and several planetary scientists selected from NASA and various universities. The latest field test was performed in the Mojave desert during May of 1997. The rover traversed over 1000 meters commanded from a trailer in the field. The operator did not have a direct view of the rover which was normally about 1 to 2 kilometers away from the trailer. This field test demonstrated the feasibility of the 2001 and 2003 long range science rovers planned for Mars.

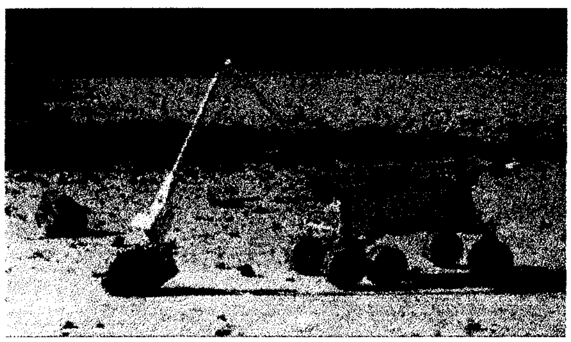

Figure 9. Rocky 7 as it placed its Moessbauer instrument on a rock.

6. REFERENCES

[1] JPL Missions: http://www.jpl.nasa.gov/
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